Forecasting the Onset of Damaging Winds Associated with a Squall Line/ Bow Echo Using the Mid-Altitude Radial Convergence (MARC) Signature

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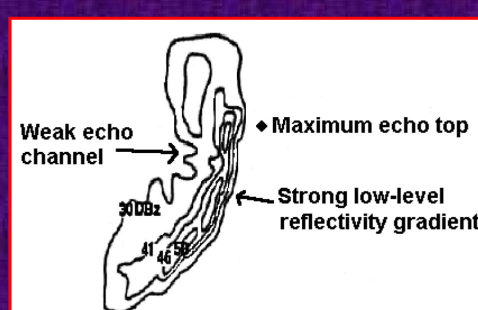
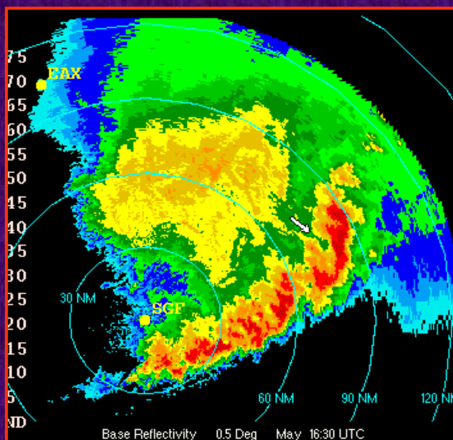
Radar Based Signatures of Damaging Winds

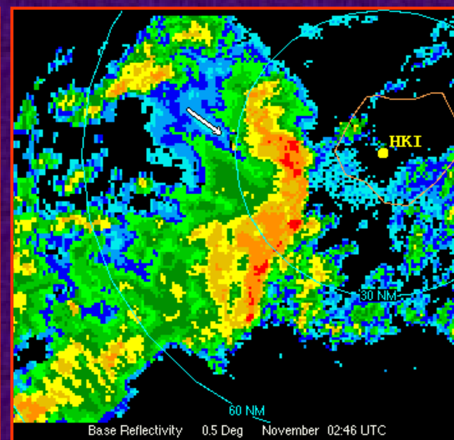
Reflectivity characteristics of a "distinctive" bow echo (Fujita, Przybylinski & Gery):

- Outward bowing of line echo
- Weak echo channels WECs)/ rear inflow notches (RINs) identifying location of rear inflow jet (RIJ)
- Strong low-level reflectivity gradient on leading edge
- Max echo top aloft usually displaced slightly downwind from low-level reflectivity for organized bows



Two Examples of Bow Echoes with Strong Low-Level Reflectivity Gradients and Pronounced WECs/RINs





A tight reflectivity gradient implies a strong updraft/downdraft interface and greater threat for continued active and potentially damaging squall line. Arrows denote locations of weak echo channels (WECs)/rear inflow notches (RINs) in the back side of the line. These are indicative of enhanced pulses in the rear inflow jet and likely locations for enhanced wind damage along the leading edge gust front.

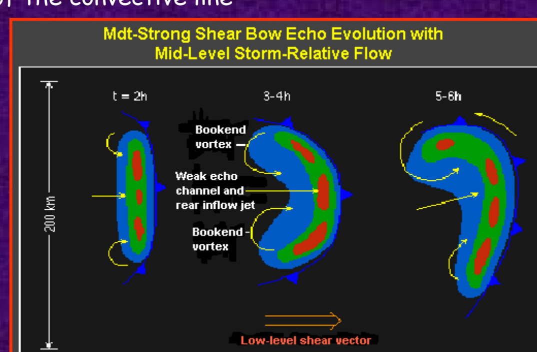
Doppler Radar Based Signatures of Damaging Winds

• High VIL values (intense storm/updraft capable of producing wind damage, but better correlated to heavy rain and/or hail)

• Base velocity of 50 kts or more at lowest elevation (limited range)

• Weak echo channels (WECs)/rear inflow notches (RINs) in reflectivity data suggest evaporative cooling and locations of the rear inflow jet (RIJ) and wind damage along the leading edge of the convective line

• Identification of vortices – strong circulations along a line can enhance low-mid level winds (RIJ); greatest wind damage often is observed along bow apex just south of the path of a cyclonic circulation (convective line typically accelerates and/or "bows out" south of a strong cyclonic circulation)

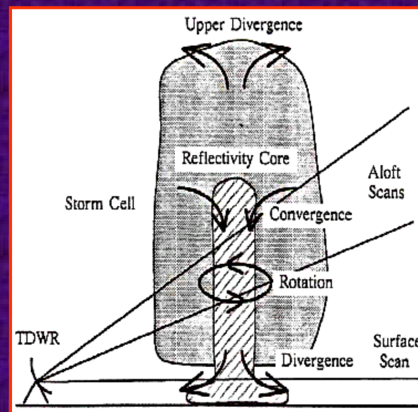


Damaging Wind Precursors Identified from Microburst Studies on Pulse Type Storms (Eilts et al. -DDPDA)

• Initial reflectivity core development at a higher height than surrounding storms (indicative of intense updraft)

• Strong mid-altitude radial convergence (MARC >22 m/s or 50 kts) associated with isolated pulse type storms (also correlated to subsequent wind damage in squall lines and bow echoes

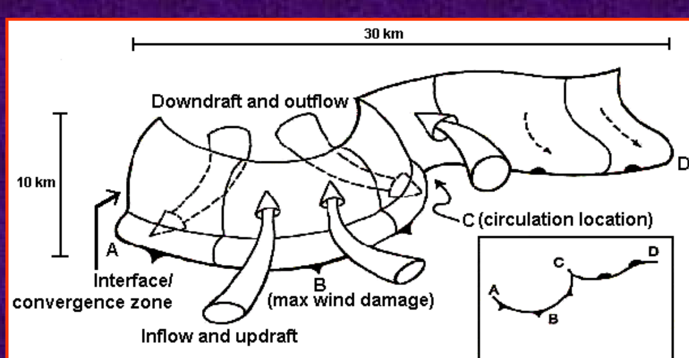
• Rapidly descending reflectivity core



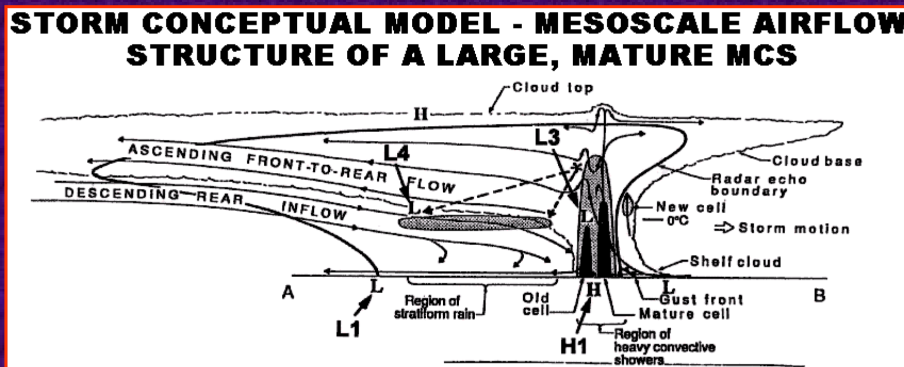
Convergent Signatures in Organized Convection - Supercells

• Deep Convergence Zone (DCZ) was identified in supercells by Lemon et al. at the interface of the updraft/downdraft currents

- this narrow zone represents a region of intense convergence and shear with an average depth of 10 km
- damaging winds often occur along or just behind the DCZ with mesocyclones and/or gust front tornadoes along it



A Review of Squall Line Mesoscale Airflow Structures



Development of RIJ attributed to mid-level, mesoscale areas of low pressure (L3 & L4; Smull & Houze,1987)
L3: Hydrostatically-induced negative pressure perturbations under upshear tilted warm convective updrafts (and above evaporatively-cooled downdrafts)
L4: Mid-level mesoscale low in the stratiform region

Dual Doppler Analysis of a Northern Plains Squall Line
(Klimowski 1994)

Observations of the mesoscale rear inflow jet (RIJ):

-Rear inflow was initiated near the high reflectivity cores of the squall line and was mainly elevated, increasing in magnitude and expanding rearward with time (RIJ average height was near 4 km MSL)

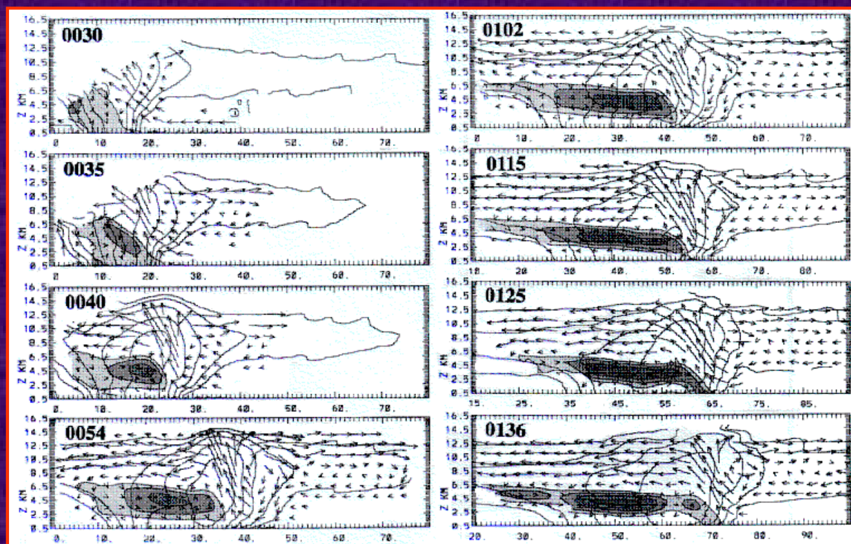
-Maximum values of the rear inflow initially were located near the high reflectivity cores at the front of the system

-Rear inflow was not homogeneous along the length of the squall line (variability in elevation and several local maxima along line existed)

-Rear inflow was stronger where trailing stratiform precipitation region formed and matured

-Slight positive correlation between the development of the rear inflow and the development of front-to-rear (FTR) flow (where RIJ was strongest, FTR usually was maximized)

Reflectivity/Velocity Cross-Sections Perpendicular to Squall Line



Reflectivity contours are solid. Shaded region represents the evolution of the mesoscale rear inflow jet (Klimowski 1994). RIJ deflects down to surface near updraft/downdraft interface along leading line.

Convergent Signatures in Organized Convection – Squall Lines/Bow Echoes

• Przybylinski et al. 1995 noted strong mid-altitude radial convergence (MARC) along forward flank of convective lines before they began to "bow out"

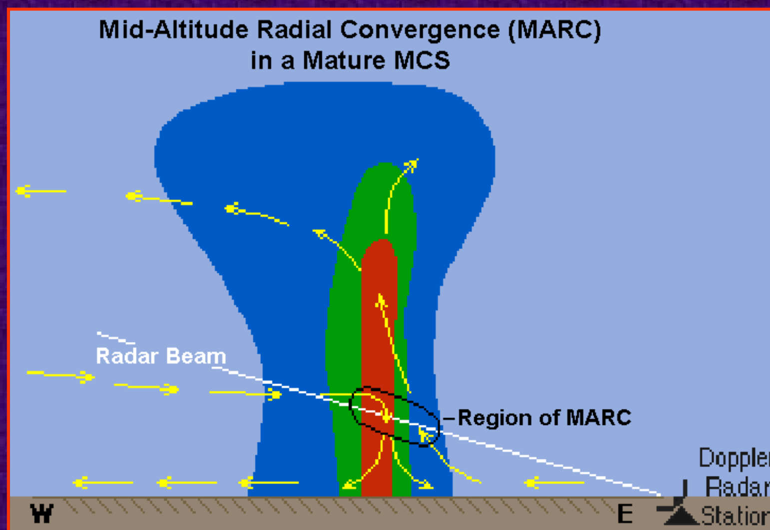
• Observations using WSR-88D to survey a component of squall line's sloping updraft/downdraft currents along forward flank of MCS during intensifying stage:

For a storm approaching from west or upstream of radar:
- region of strong outbound velocities signifies a component of the storm's updraft current and front-to-rear flow
- region of strong inbound velocities depicts the storm's convective scale downdrafts and origins of the mesoscale RIJ

For a storm departing to east or downstream of radar:
- region of strong inbound velocities signifies a component of the storm's updraft current and front-to-rear flow
- region of strong outbound velocities depicts the storm's convective scale downdrafts & origins of the mesoscale RIJ

For a storm moving nearly perpendicular to the radar: MARC may be difficult to discern (due to the viewing angle), but may still be present (so BEWARE)

MARC in a Mature MCS



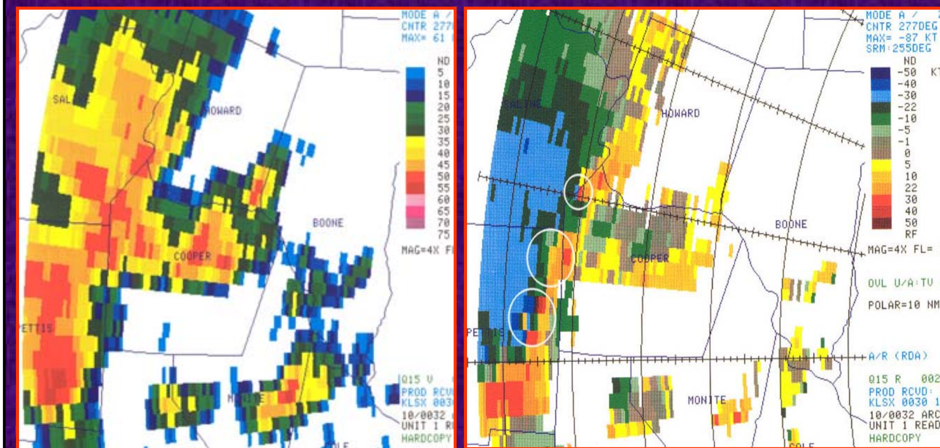
MARC Dynamics

• Persistent areas of strong radial convergence (enhanced convergent velocity differentials) within the larger zone of convergence along the forward flank of the convective line appears to be linked to the greatest degree of wind damage

• These persistent areas of strong radial convergence (the MARC velocity signature) are usually located in or just downwind of the high reflectivity cores along the leading edge of the line

• These enhanced areas of convergence usually are less than 15 km in length and less than 7 km in width. A strong velocity gradient between the inbound and outbound maxima (nearly gate to gate) yields the strongest actual convergence

Example of MARC in a Developing Line Echo



White circles enclose 3 MARC velocity signatures - enhanced spots of convergence within an elongated zone of convergence along the forward flank of the linear convective system over central MO (west of St. Louis radar site KLSX)

More MARC Dynamics

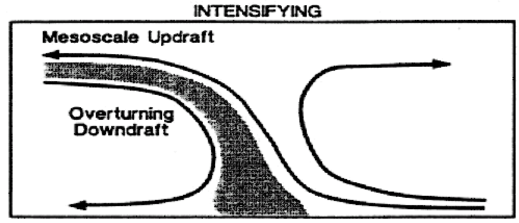
• Once radial velocity differentials reach 25 m/s (50 kts) or greater (actual convergence values of 2.5 x 10-2 to 5.6 x 10-3 s-1), the potential for severe straight line winds increases

• Radial Convergent Velocity Difference = |V(inbound)| + |V(outbound)|

• Actual Convergence = (|V(inbound)| + |V(outbound)|) / (Distance between convergent isodops along radial)

• Convective-scale vortices (tornadic and non-tornadic) often form in the zone or interface between the two drafts (mainly on the updraft side) where cyclonic or negative horizontal vorticity is strong. A cyclonic circulation sometimes develops on the northern end of a MARC signature

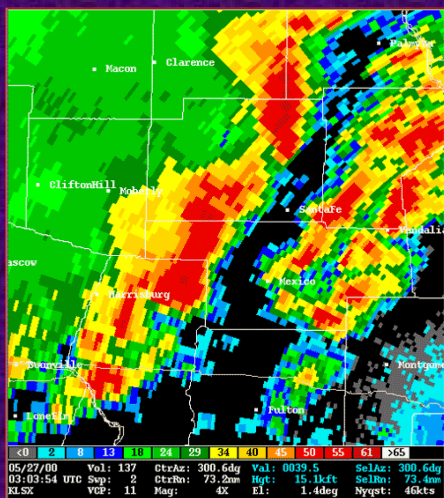
INTENSIFYING

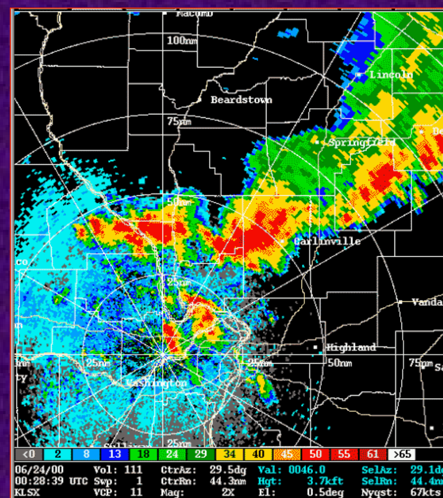


Schematic diagram of the 'Intensifying Stage' of squall line flow features adapted from Thorpe et al. (1982). Vorticity zone is shaded region.

Reflectivity Characteristics & the MARC Signature

The MARC velocity signature has been observed more frequently with a nearly solid linear convective segment (left) than with discrete convective cells along the southern flank of an asymmetric MCS (right).





Case Sample & MARC Characteristics

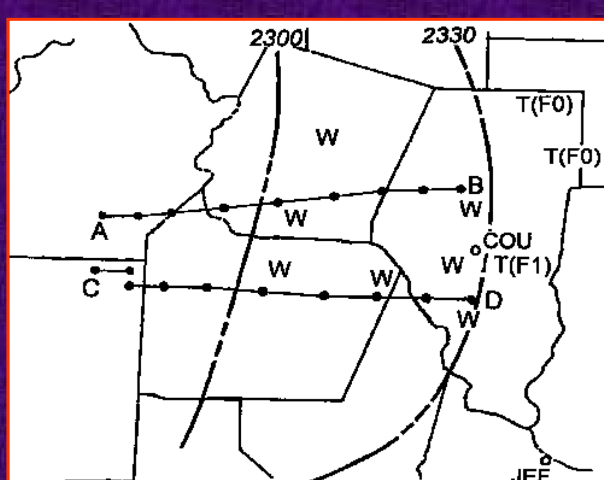
16 warm season (May-September) MCS cases studied so far

Cases (1992-2000)	Instability/Shear (0-3 km bulk shear)	Initial Hgt of Marc (km)	Strongest Mag (m/s) and Height of MARC (km)	Horizontal extent of Convergent area (km)	Vertical Extent of MARC (km) & Mean Hgt(km)	Lead Time (min)
9 afternoon/ evening	2200-5000 J/Kg 3458 J/Kg 10 -17 m/s 13.7 m/s	2.4 - 7.3 Km 4.7 Km	26 - 55 m/s 39.5 m/s 1.9 - 7.3 Km 4.6 Km	50 - 160 Km 83 Km	2.8 - 6 Km 4.4 Km 3.3 - 6.3 Km 4.7 Km	3 - 80 min 21 min
5 late night/ early morning	2006-4000 J/Kg 3150 J/Kg 11 - 20 m/s 16.4 m/s	3 - 5.2 Km 4.4 Km	27 - 45 m/s 34.6 m/s 2.4 - 6.6 Km 4.1 Km	35 -75 Km 50 Km	1.4 - 5.4 Km 3.5 Km 3.0 - 5.7 Km 4.4 Km	1 - 39 min 14.2 min
All 16 cases 9 afternoon/ evening 5 late night/ early morning 2 mid-late morning	2006-5000 J/Kg 3352 J/Kg 10 - 20 m/s 14.7 m/s	2.4 - 7.3 Km 4.5 Km	26 - 55 m/s 37.5 m/s 1.9 - 7.3 Km 4.3 Km	35 - 160 Km 75 Km	1.4 Km - 6 Km 4.0 Km 3.0 - 6.3 Km 4.6 Km	1 - 80 min 18.7 min

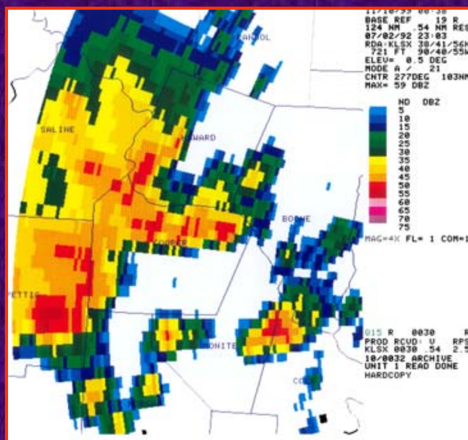
Differences Between Afternoon/Evening and Nocturnal (Late Night/Early Morning) Cases

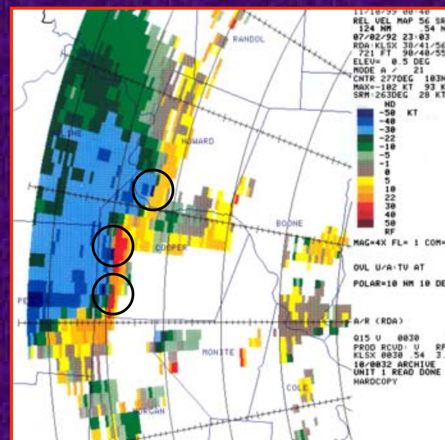
- Afternoon/evening cases typically occur in environments with greater CAPE but less 0-3 km shear
- In nocturnal cases, MARC tends to be weaker, shallower, and found at a lower height
- The horizontal extent of the overall convergent region along the forward flank of the convective line also is less in the nocturnal cases
- The MARC signature has shown greater lead time in the afternoon/evening cases

Case Example #1 – July 2, 1992 (high instability & moderate shear) MARC tracks & initial wind damage reports (W)



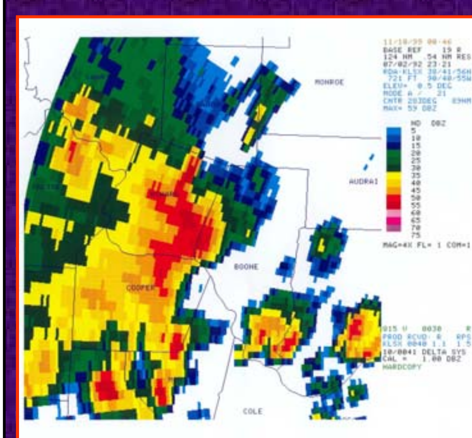
0.5° Reflectivity/SRM Velocity Images at 2303 UTC

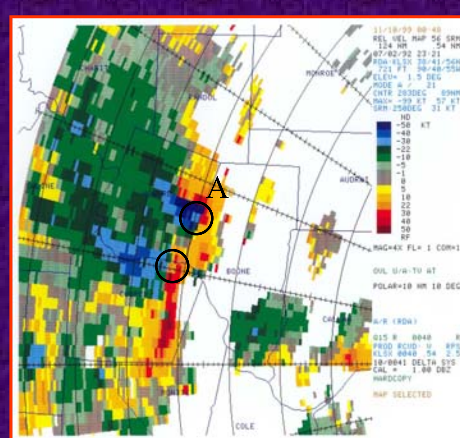




Strong MARC signatures (within black circles) were evident on the leading edge of the developing line echo

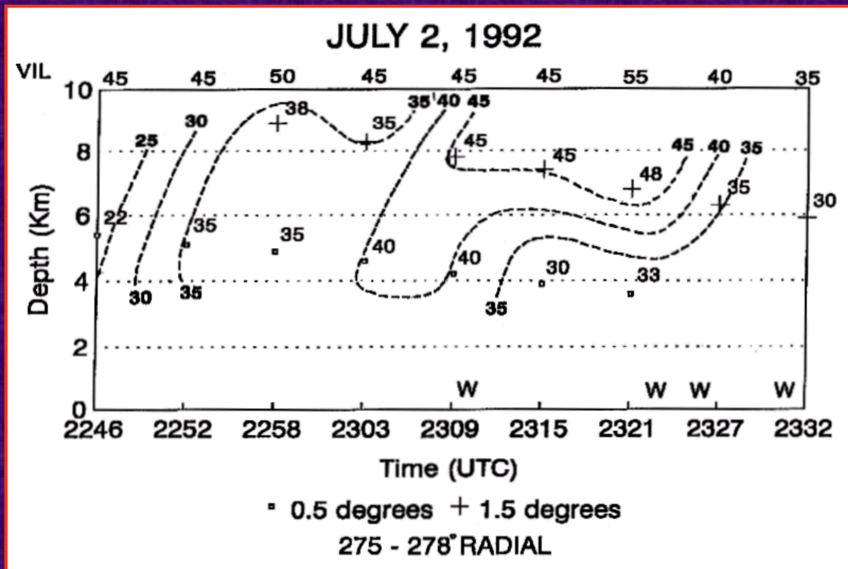
2321 UTC Reflectivity (0.5°) and SRM Velocity Image (1.5°)



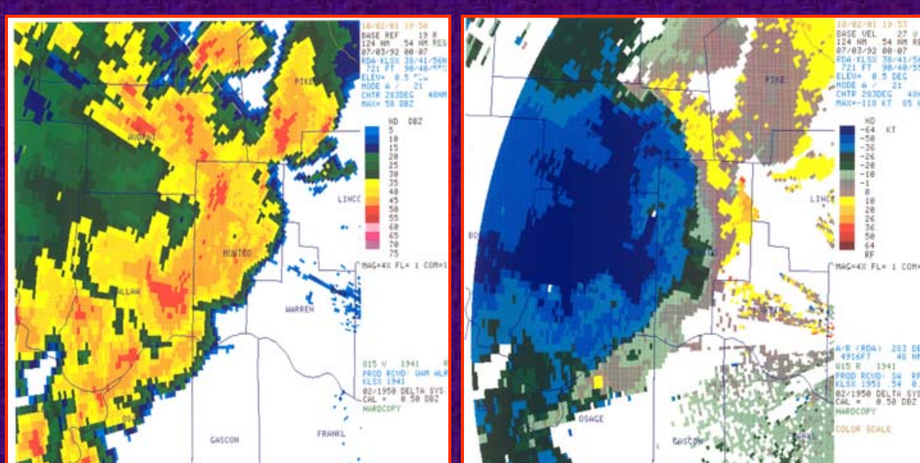


Bow echo has developed with 2 MARC signatures (within black circles) south of strong cyclonic vortex (near "A")

Time-Height Section of Southern MARC (m/s) Signature
(VIL is plotted on top; W denotes times of wind damage reports)

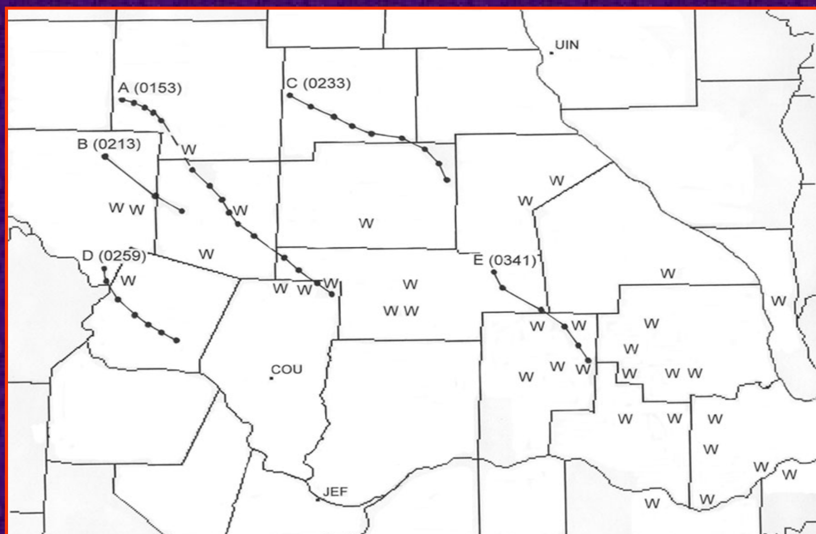


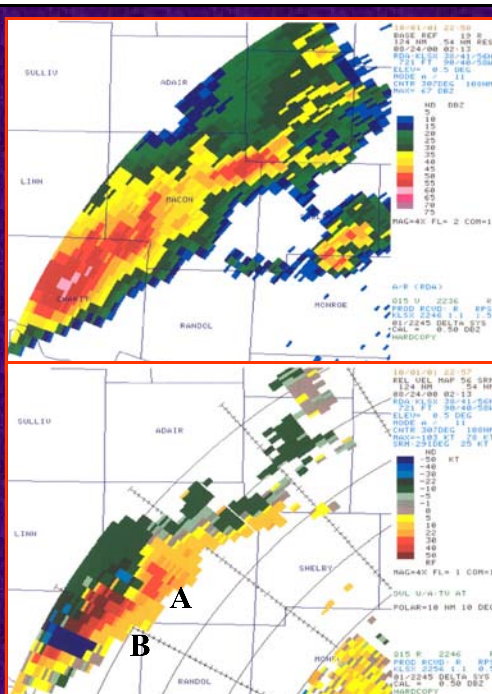
0.5° Reflectivity/Base Velocity Images at 0007 UTC



Reflectivity shows that within an hour (2303 to 0007 UTC), the MCS evolved into a large, mature bow echo with a large area of greater than 64 kt inbound winds (RIJ; dark blue in velocity image) at 5-6 kft height northwest of the St. Louis radar site KLSX). Thus, the MARC signature provided advanced clues that a bowing segment and enhanced surface wind damage would develop.

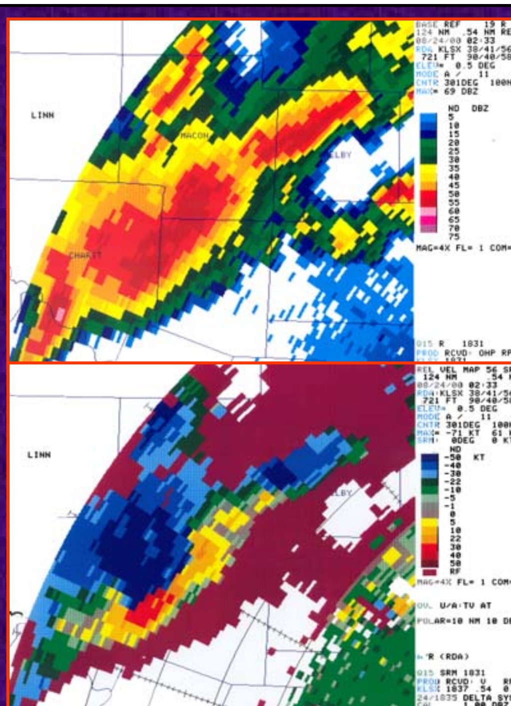
Case Example #2 - August 24, 2000
(high instability & weak shear)
MARC tracks and wind damage reports (W)





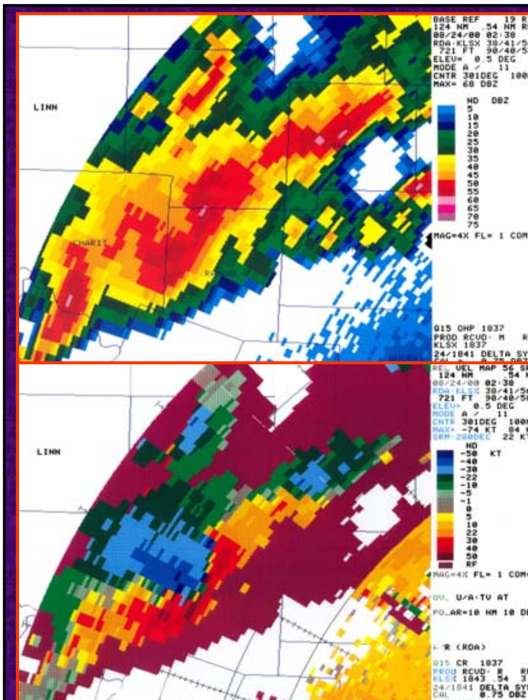
0213 UTC 0.5° Reflectivity and SRM Velocity Images

0.5° images over central MO showed an MCS with 2 MARC signatures (near locations A and B) in the developing line segment; these MARC signatures denote the updraft/ downdraft interface in the MCS (MCS is located to northwest of radar site).



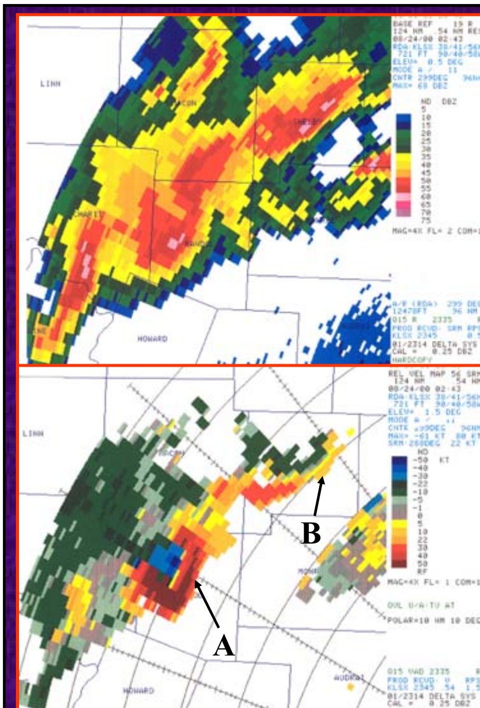
0233 UTC 0.5° reflectivity and SRM velocity images

0.5 ° images 20 minutes later over central MO displayed strengthening MARC signatures (between dark blue inbounds and orange and red outbound colors) as the RIJ (dark blue) intensified; a weak echo channel was developing on the back side of the MCS in reflectivity data.



0238 UTC 0.5° Reflectivity and SRM Velocity Images

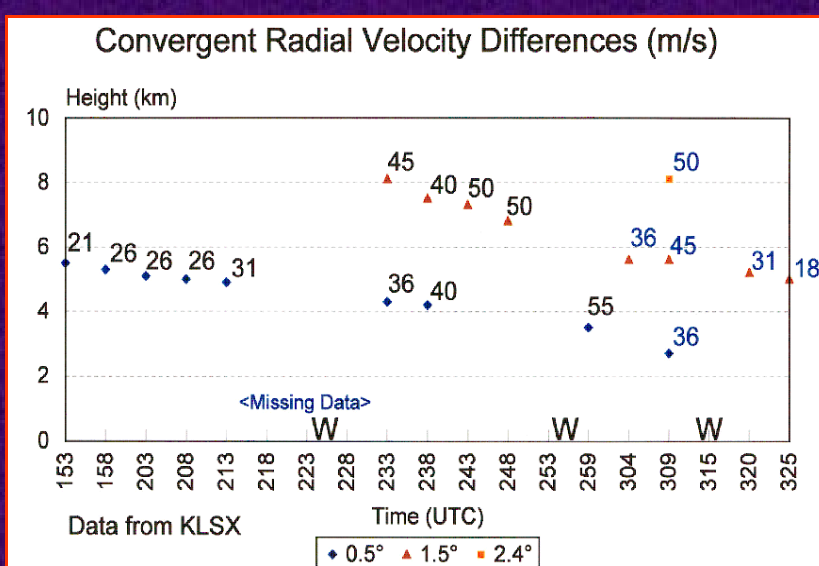
0.5 ° images one volume scan later showed several important signatures: 1) strong MARC along the leading edge of the developing bow echo; 2) a well-defined RIJ (dark blue) coincident with a well-defined weak echo channel in reflectivity data; 3) since the MCS was moving toward the radar, actual RIJ strength (winds) were greater than shown in the SRM image since system speed was subtracted out from displayed values (use base velocity to determine actual speed); 4) broad cyclonic and anticyclonic vortices (“bookend” or “line end” vortices) were present on either side of the RIJ, which can accentuate the RIJ.

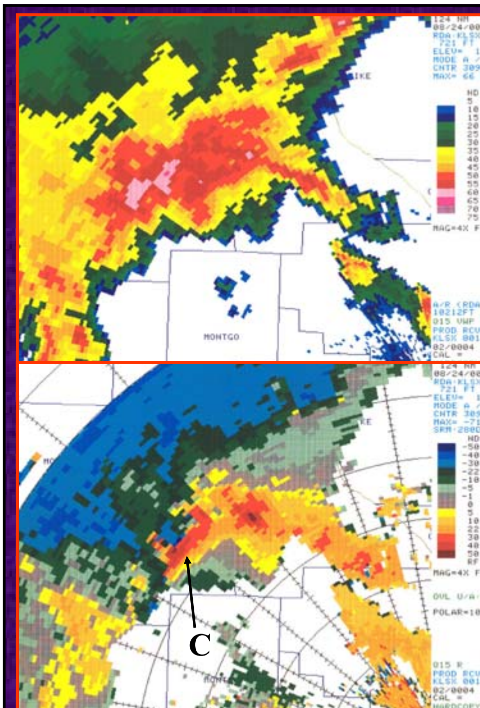


0243 UTC 0.5° Reflectivity and SRM Velocity Images

0.5° images showed a weak echo channel (WEC) in reflectivity data coincident with strong inbound winds (i.e., the RIJ; dark blue) in SRM data. Impressive MARC still was present along the updraft/ downdraft interface (location A), indicative that damaging downburst winds likely would continue at the surface. MARC also was present at location B along the leading edge of another active portion of the MCS, although displayed MARC values were weaker. However, beware that a less effective viewing angle may preclude accurate measurement of actual MARC values and subsequent downburst potential.

August 24, 2000 MARC Vertical Cross-Section Trace

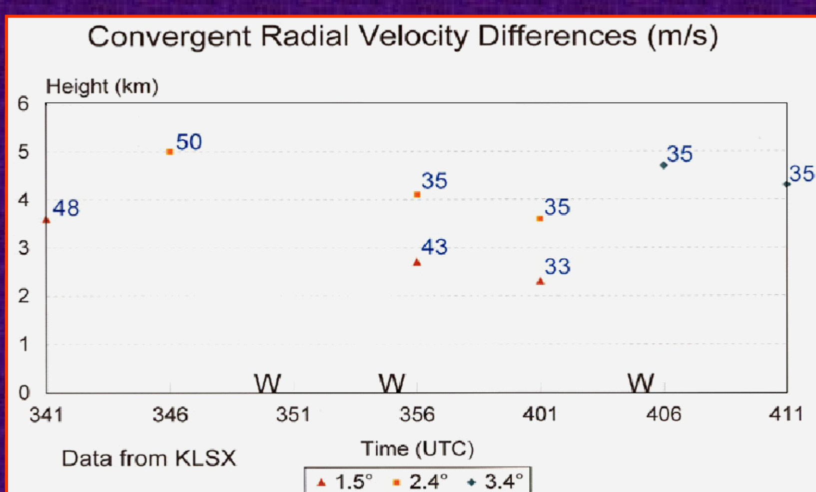




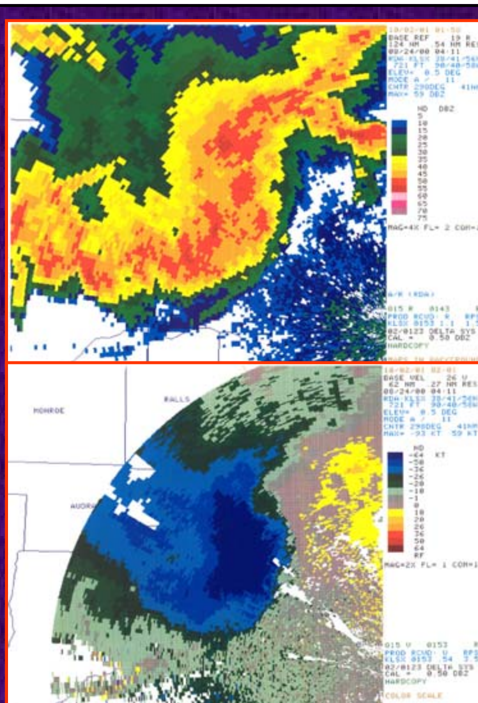
0341 UTC 1.5° Reflectivity and SRM Velocity Images

1.5° images at 0341 UTC showed that a new MARC signature (location C) rapidly developed just ahead of a 60-65 dBZ core in the large convective cluster; although the cluster showed little evidence of bowing at this time, the strong MARC signature aloft provided a critical clue and heads-up that subsequent bowing and surface wind damage might occur. Thus, proper identification and evolution of MARC is crucial to provide valuable lead time in issuing or extending severe weather warnings for wind damage; subsequent downbursts then can even lead to low-level cyclonic circulation spin-up and tornado development.

August 24, 2000 MARC Vertical Cross-Section Trace: Location C



Note that significant MARC values from about 3-6 km altitude preceded the first report of damaging surface winds by several minutes



0411 UTC 0.5° Reflectivity and Base Velocity Images

By 0411 UTC, 0.5° degree reflectivity and *base* velocity images depicted a large, mature bow echo with an area of strong inbound winds (>64 kts…radar indicated a 93 kt maximum inbound value) at about 4 kft altitude northwest of the KLSX radar site. Thus, the strong MARC signature at 0341 UTC in conjunction with developing rear inflow indeed resulted in subsequent intense downburst activity that led to development of an intense bow echo and damaging surface winds.

Damage Pictures From a Storm Survey Across Warren and Montgomery Counties Northwest of St. Louis

Damage to roof (sheet metal) of school in Wright City

Damage Pictures

Below: Tree damage near a church in Montgomery County

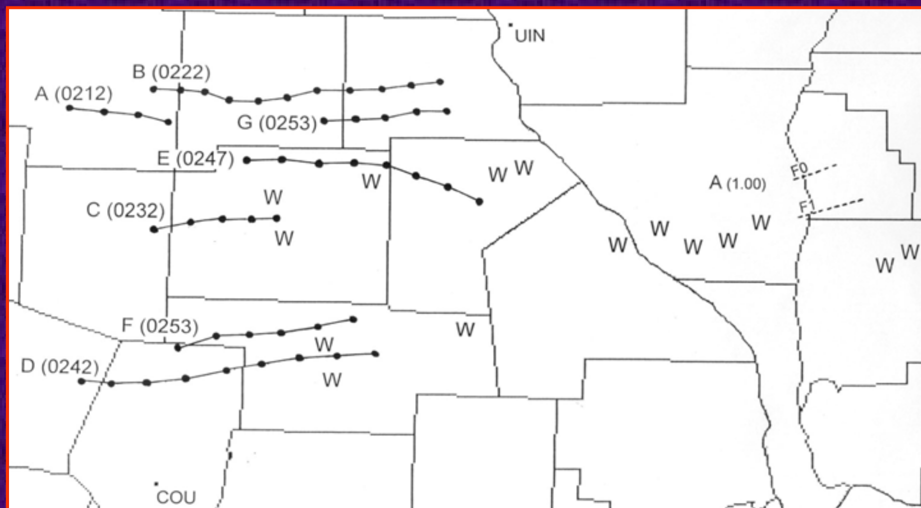
Above: Tree damage near Bellflower in Montgomery County

Damage Pictures

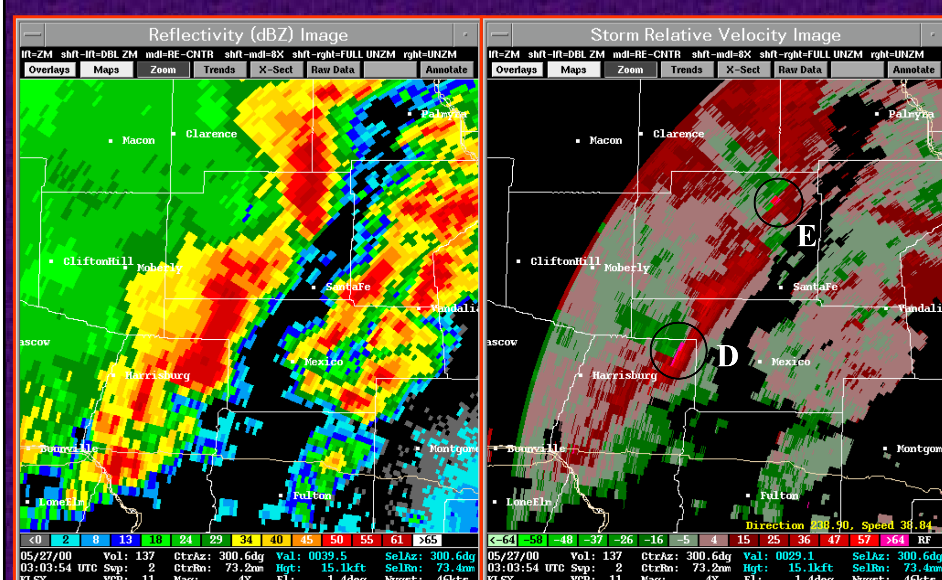
Above: Machine shed blown down east of Bellflower

Above: Small house trailer blown over east of Middletown

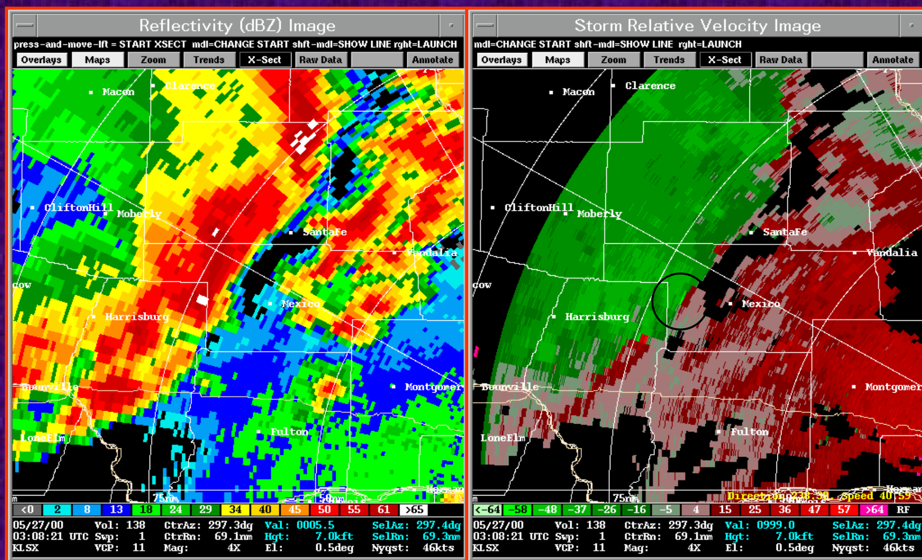
Case Example #3 – May 27, 2000
(moderate instability & moderate shear)
MARC tracks and wind damage (W)



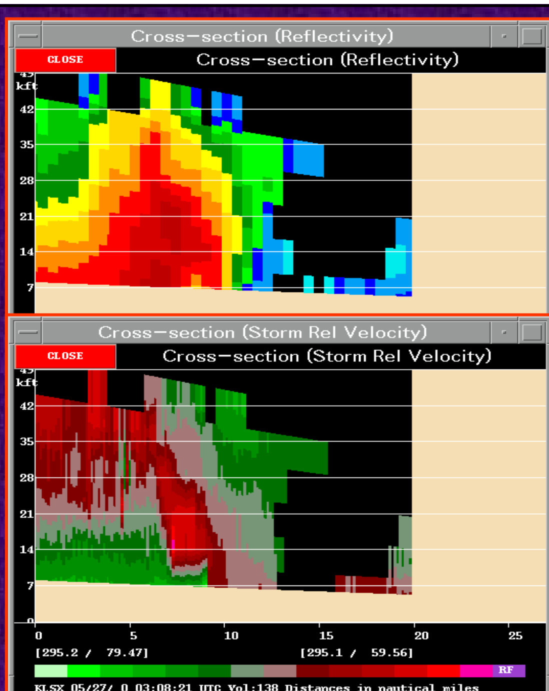
1.5° Reflectivity/SRM Velocity Images at 0303 UTC:
Note 2 distinct MARC signatures (tracks D and E)



0.5° Reflectivity/SRM Velocity images at 0308 UTC (Let's cut a cross-section through MARC signature D)



0308 UTC Reflectivity and SRM Velocity Vertical Cross-Section

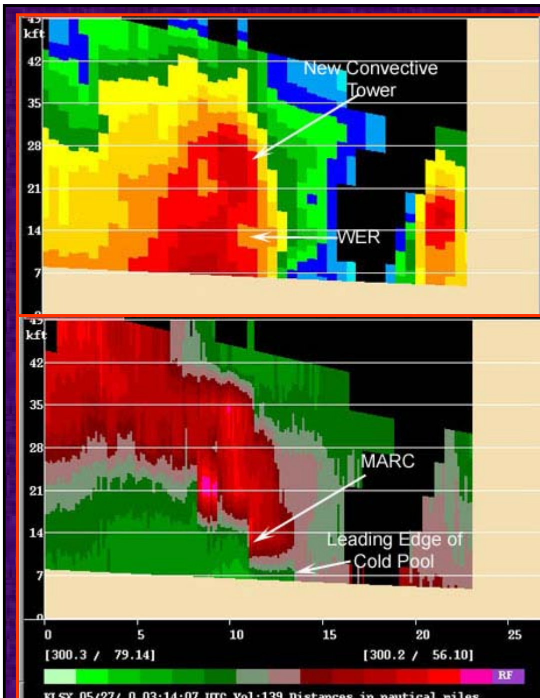


Reflectivity and SRM velocity cross-sections at 0308 UTC. Note the significant MARC at the top of the MCS's outflow (gust front) around 7-10 kft surging ahead of the convective towers. Note also the vertical updraft zone (red outbounds) within the active convection and the more gentle front-to-rear system-relative ascent in the stratiform area behind the leading line and above lower-level rear-to-front flow (green inbound colors).

1.5° Reflectivity/SRM Velocity Images at 0314 UTC

Blue arrows point to 3 MARC signatures (locations D, E, and F)

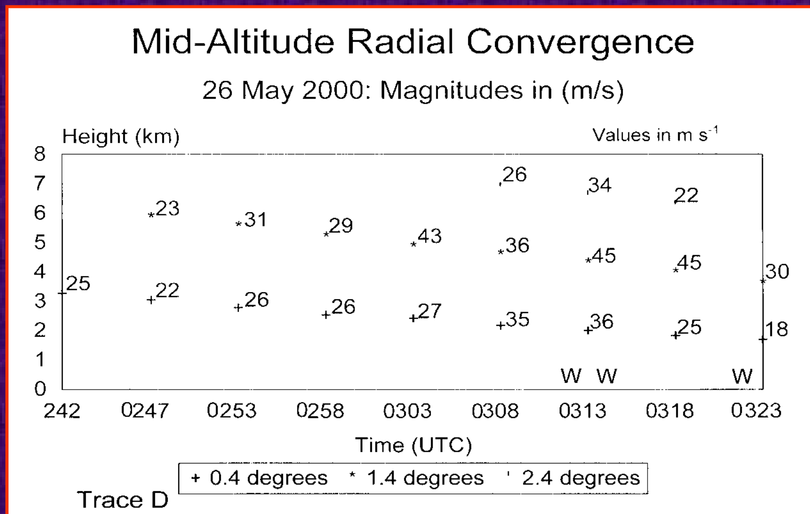
Let's cut another x-section through D



0314 UTC Reflectivity and SRM Velocity Vertical Cross-Sections

Cross-sections at 0314 UTC depicted the top of the MCS's surging outflow (gust front) around 7 kft, where rear-to-front flow was undercutting and surging ahead of elevated MARC from (10-15 kft); also present were a local outbound velocity maximum embedded within front-to-rear flow around 21 kft, and a well-defined system-relative front-to-rear stream behind the active convective region associated with trailing stratiform precipitation.

Time-height Section of MARC Signature "D"



Again, MARC was noted well before the first report of surface wind damage, and MARC values generally increased leading up to this report

Summary and Key Findings

- The MARC velocity signature (i.e., inbound/outbound velocity differential along the same radial) values of greater than or equal to 25 m/s or 50 kt provided average lead times of almost 20 minutes prior to the first report of damaging winds.

- MARC often was identified before development of a well-defined bow echo or strong vortices (mesocyclone or line-end/bookend vortices)

- MARC usually was identified at a height between 4-5 km (12-17 kft) along the forward flank of the convective line (in or just downwind of the high reflectivity cores within the line).

- Since it is a mid-level signature, it can be detected as far as 120 nm from the radar using the lowest elevation slice.

- The MARC velocity signature has been observed more frequently with a nearly solid linear convective line compared to discrete convective cells along the southern flank of an asymmetric MCS (viewing angle may be a factor).

Summary and Key Findings

• Preliminary results indicate that the MARC signature is not as identifiable with nocturnal convection compared to convection occurring during the afternoon/evening hours (weaker magnitudes and shorter lead times have been observed with the nocturnal cases examined so far, but more cases need to be studied).

• Importance of the viewing angle: MARC will be underestimated when the convective line is not orthogonal (perpendicular) to the radial.

•When evaluating MARC and subsequent wind damage potential, you must understand the environment it is occurring in. Even with a strong MARC signature, damaging surface winds are less likely if a deep (greater than or equal to 2 km), cool, stable boundary layer is present (i.e., convection is not surface-based but is elevated north of a stationary/warm front).

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For further MARC information and other damaging wind studies, go to: www.crh.noaa.gov/lsx/science/newcomet.htm